Developing an Operational Automated Real Time Tunnel Monitoring System

G. H. Tan
SysEng (S) Pte Ltd

K. G. Chua
Wisescan Engineering Services Pte Ltd

ABSTRACT: In cities with tunnel networks and adjacent construction works, the tunnels require real time monitoring and immediate alert systems when their movements exceed their allowable limits. Automated system provides reliable and consistent data. However the measured data are stored locally on site and can be retrieved only at weekly intervals during the night when the trains are not operating. This valuable data is useful as engineers use them to monitor the tunnel movements in almost real time during the critical phase of the project. New innovative technologies of smart Remote Terminal Units, Wire-less communications and Mobile phone SMS alerts are introduced to fully automate the system to send the measured data to the right person and alert the responsible person for any corrective actions to be undertaken. The paper will discuss the integrated multi-discipline system approach and the challenges in implementing an outdoor fully automated real time tunnel monitoring system used in Singapore by exploiting Information Technology and Wireless communication systems.

1 INTRODUCTION

In cities with operating tunnel networks, the construction works near these tunnels require real time continuous tunnel monitoring systems. These systems provide these important data immediately for decision making, and then sending out alerts if the tunnel movements exceed the allowable design limits. A fully automated measuring system with real-time data communication system will provide immediate reliable information to the relevant contractors, consultants and authorities simultaneously. However in many cases, these automatically measured data are stored in the on-site system. These data are retrieved manually during the night when the trains are not operating. Alternatively they can also be manually retrieved via wire-less methods from the sites. As the measured data are retrieval and analyzed manually, human errors and time delays do occur. Hence, this crucial information can be up to 24 hours late and precious time can be lost if the movements deviate from their allowable limits. New innovative technologies of smart Remote Terminal Units (RTUs), Wire-less communications and Mobile phone Short Message Service (SMS) alerts are introduced to the automated tunnel monitoring system. With these enhancements, the measured data are automatically analyzed for the right persons and SMS alerts are sent to the persons for corrective actions. As tunneling works 24 hours a day and 7 days a week, any monitoring required has to follow the same tunneling effort to avoid expensive construction delays.

The paper will discuss an integrated system design approach and the challenges in implementing an out-door fully automated tunnel monitoring system with immediate automatic data analysis and SMS alerts used in Singapore by deploying eMonitoring systems (Tan 2000), which synergies both IT and Wireless technologies together.

The Leica Total Station TCA2003 is the key instrument in the tunnel for the X, Y, Z coordinates measurements using prisms mounted along the tunnel. This instrument has been used extensively before and is a proven instrument for such monitoring applications. The first fully outdoor-automated wire-less system was developed for the LTA C5423 Changi Airport Runway 1 project in 2000. This paper discuss about the challenges in designing a robust automated real time tunnel monitoring system used in the LTA C825 Circle Line Tunnel Monitoring system (2002). The Infocomm Development Authority of Singapore supported this project under the Call for Collaboration Program on Mobile workforce solutions (IDA 2000) as an Innovative IT and wire-less Solution deploy in the construction industry.

2 SYSTEM

In any system design, the functional flow of data can identify the critical component in the information flow chain, as the weakness or the slowest component defines the limits of the system. As a benchmark, two automated wireless systems performances are discussed. With the automation and wire-less technologies accessible in Singapore, the benefits of deploying an automated tunnel monitoring system can be achieved with immediate results rather than depending upon manual data retrieval and manual analysis processes. Manual processes are unreliable, have high error rates and slower response times to urgent alerts.

2.1 Automated Wireless system A with Manual data retrieval and manual alert system

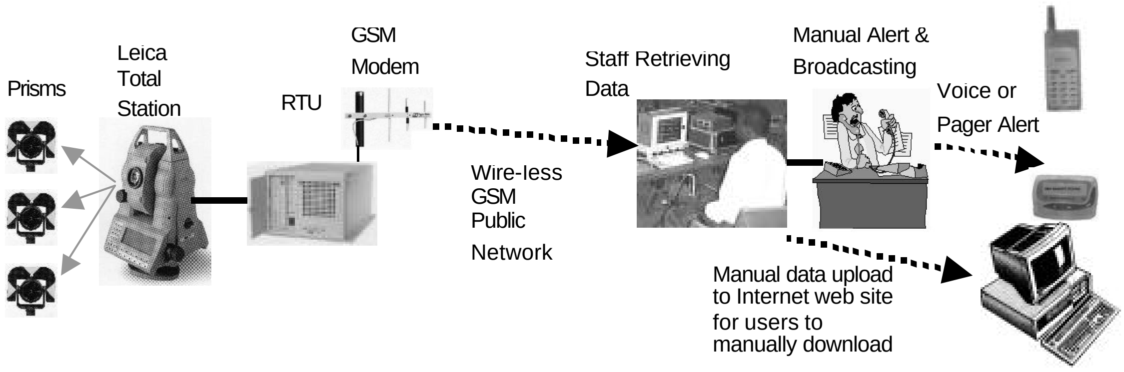

Fig 1 Measurement and Communication process steps of System A

The first system A (Fig. 1) consists of Leica Total Station, RTU, GSM modem, a staff with a computer dialing into the RTU to extract the measured data. He then analyze this data, call the end users to alert them if the movements exceed the limit and then uploading these results to a Internet web server for users to manually download. This system depends on the human to pull the information from the remote site and then push the information to users. As the measurement cycle has a wide time spread due to outdoor conditions, the time when the measurement cycle ends is not exact. Hence the time at which the staff has to call into the RTU to extract the data is inconsistent, as he does not know exactly when to call into the RTU. This can cause lapses in timely information to the end users.

2.2 Automated Wireless system B with automatic data retrieval and automatic SMS alert system

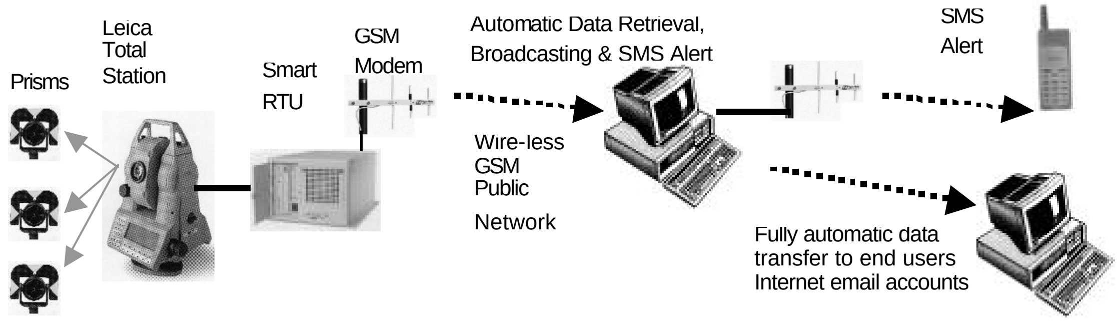

Fig. 2 Measurement and Communication process steps of System B

The second system B (Fig. 2) consists of Leica Total Station, Smart RTU, GSM modem, an automatic computer system which receives the measured data, automatically analyzing the measured data, automatically Internet emailing the results to users and automatically SMS alert users when the movements exceed the limit. This design is a fully automatic information push system from the remote site to the users to achieve the fastest information flow for time critical monitoring.

2.3 Comparison of the two systems

Table 1 shows the comparison of Systems A and B in information flow. It identifies the steps where humans are involved and they form the weakest and inconsistent part of the information flow chain. During the initial monitoring setup phase, the flow of information is less critical as during this monitoring period is used to set the datum line. As the work progresses into the critical phase, the frequency of monitoring increases and the flow of information becomes faster. Hence system reliability and respond time becomes important to avoid construction failures. As the humans are involved in these demanding process steps, it is very difficult to maintain consistency in the Quality and Timely information to the users.

Table 1 Comparison of Systems A and B

Process Steps	System A	System B
Leica Auto Total Station	Yes	Yes
RTU	Yes	Yes
Wire-less Communication	Yes	Yes
Data Retrieval	Human	Automated
Data Analysis	Human	Automated
Data Sending & Alert	Human	Automated

For information to flow from the remote site to alert the end user, there are 6 process steps in the information chain as shown in Table 1. If any of these steps are broken or delayed, then the information system flow is disrupted. In any system, the human factor is always the weakest part as it is not a consistent element. Hence system B is a more suitable system for a reliable automated tunnel monitoring system such that the user has almost immediate data once the measurements have been completed.

For long term continuous monitoring of critical assets, which requires 24 hours and 7 days operations over 2 years, the manual effort is an expensive and not a practical solution to sustain as it imposes challenges to the management, rotating work shifts and Quality of monitoring specialist teams.

3 DESIGN CHALLENGES FOR A FULLY AUTOMATED SYSTEM

3.1 Wireless communication in tunnel

At the monitoring site, the RTU sends the measured data to the office computer system using GSM data network. Ideally, telephone line is a preferred choice due to reliability and speed advantages. However in most MRT tunnels, the costs of cabling additional telephone lines to the temporary monitoring sites are just too high to be considered. Hence wire-less GSM lines are more cost effective for real time applications. It was found that the GSM signal disruptions are site dependent. This signal disruption increases the time to transfer the measured data file as the number of error correction increases within that transmission duration. For some cases, the signal disruption is so high that the GSM signal line is cut off completely. A few possible causes for this interruption could be the train attenuating the GSM antenna signals and the high EMI generated from the power lines overloading the front-end amplifiers of the GSM modem. This requires a GSM line re-connection, hence restarting the file transfer and delays the file transfer process. In a manual system, the human user intervenes if the GSM signals level drops and the user just reconnect the line. In some cases relocating the GSM antenna position improves the situation. However in a fully automated system, the challenges are greater as the software and hardware error recovery methods must have intelligence built–in to handle any exception events.

In a tunnel-monitoring site, the GSM RF signal strength levels are logged over a week and analyzed for the signal disruptions, as during initial trials the file transferred took longer than expected from its ideal time.

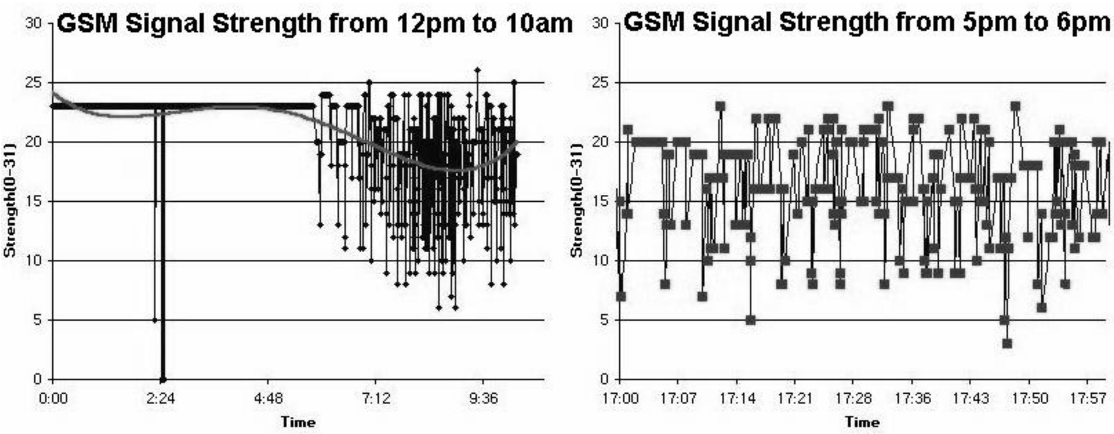

Fig. 3 GSM signal strength variation in time

Figure 3 shows that from midnight to 5 a.m., the signals strength are high and have little disruption except at 2.20 a.m. when the power was switch off for maintenance purposes. In normal times when the MRT trains move, the signals have frequent disruptions. By examining the signal strength levels from 5 p.m. to 6 p.m. when the trains are more frequent, it can be seen that the signal disruptions occur almost every 5 minutes, which coincides with train movement frequencies. This signal disruption occurs almost every 5 minutes for the whole day except only when the trains are not operating. Hence getting reliable GSM signal strength for data transmission posed a great challenge to obtain real time automated data transfer from the tunnel.

3.2 Solution to the communication challenge in tunnel

Sometimes relocating the GSM antenna improves the situation. But a more reliable technique is to develop a robust communication protocol suitable for noisy environment. The data packet transmission algorithm in a circuit switched GSM data line configuration was developed to overcome this challenge, which occurs within the tunnel. With this method, only the affected packet data, which has been corrupted, are resent only. This data communication algorithm has help to ensure that the on-site RTU data is always sent out of the tunnel even in the event of high signal disruptions and has set a new benchmark for real-time monitoring systems.

Table 2 Transmission times and duration

	South B: File size 95 KB	
Date	Time	Duration(m)
13-Jun-03	06:36	3
13-Jun-03	14:41	5
13-Jun-03	22:59	5
14-Jun-03	06:29	5
14-Jun-03	14:54	2
14-Jun-03	22:49	4
15-Jun-03	06:29	3
15-Jun-03	14:54	5
15-Jun-03	22:39	3
16-Jun-03	06:29	3
16-Jun-03	14:44	4
16-Jun-03	22:56	4
WIth GSM @	9,600	Bits / sec
Ideal rate is	9	Bits / Byte
File Size(95KB)	855,000	Bits
Ideal Time (95KB)	1.5	mins

For C825 Southbound tunnel monitoring project, there are 24 (segments) x 4 (prisms) reference measurement points and 204 (segments) x 4 (prisms) monitoring points being measured three times per day. The measured data file size is 95 Kbytes per measurement cycle. The Table 2 shows the consistencies in the transmission times and file transmission duration. Using GSM data transfer in an ideal noise free condition, the time is only 1.5 minutes.

Before the data transmission algorithm was used, the timings to receive the file can be delayed up to 1 hour or more. Hence these unreliable receiving times are unacceptable to the users, as the real time measured data could not be analyzed and alerts are late.

3.3 Automatic Supervisory system

In the automated system and without any human intervention operating for 24 hours day, automatic supervisory systems are installed at the RTU and incoming PC system. An automatic supervisory system consists of the monitoring modules for the RS485 lines, modems, RTU system status and RTU Temperature. Upon the detection of problems in these, the software will activate the hardware reset for the related nodule.

3.3.1 RTU Automatic Supervisory system

The following supervisory modules are introduced to achieve higher reliability as outdoor conditions have many unpredictable challenges when the system suitable for indoor conditions moves to the real outdoor conditions.

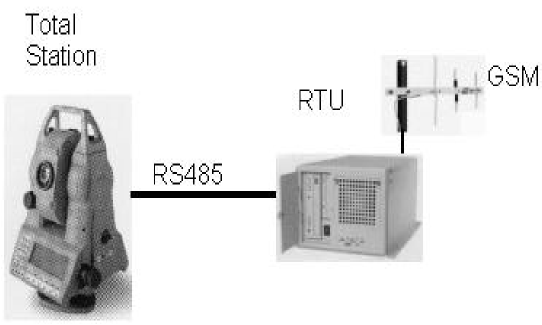

Fig. 4 Total Station– RTU sub system

As the data communication from the Total station to the RTU uses RS485, a RS485 data signal is analyzed for response. If the data line does not respond, the RS485 converter and Total station is reboot. The RTU has a watch dog timer inside to check that the computer operating system does not freeze. It does an automatic self re-boot if the computer freezes. This freeze can even occur after installing UPS, surge protection, proper grounding as the freeze can occur due to Electro Magnetic Interferences. The tunnel environment is not an ideal condition for electronics, and hence the system is designed to cater for this operating condition. The GSM communication module is interrogated for its signal strength and does a modem power reboot if it does not respond.

3.3.2 Incoming PC Automatic Supervisory system

The supervisory program monitors the status of the incoming PC modem, LAN, Internet and SMS transfer module. The incoming PC has a watchdog timer inside to ensure that the computer does not freeze. It does an automatic system re-boot if the computer freezes. The SMS communication module is interrogated for its signal strength and does a power reboot if it does not respond.

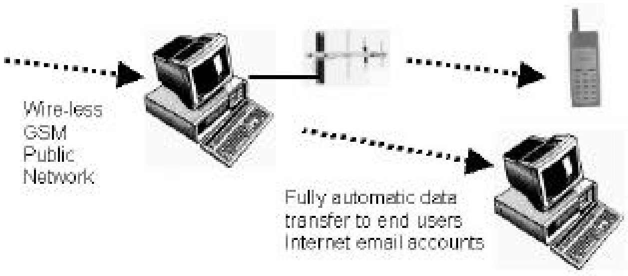

Fig. 5 Incoming PC Automatic Supervisory system

3.4 Automatic Data Trend Analysis and Alert

Inside the tunnel, each tunnel segment has 4 prisms mounted on its inner diameter. Due to mounting constraints, the prisms are mounted in an uneven angular positions as seen in Fig 6 (the bright spots are the prisms reflection from the camera flash light). During each measurement cycle, the prism X,Y,Z positions are measured and then corrected with the reference prisms. Only the X and Z-axes movements are of major interests. The measured data are chart on every cycle for its X and Z movements. The SMS alert is triggered when the X or Z movements exceed 5.0 mm from its set datum limits.

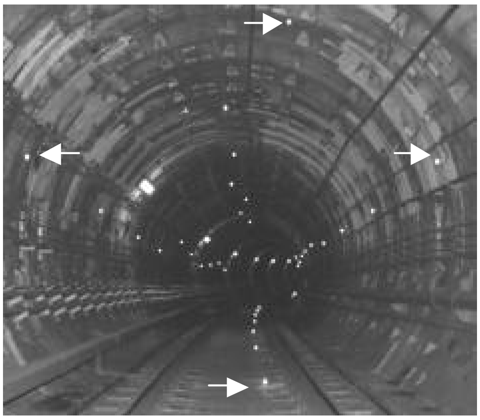

Fig. 6 Picture of Tunnel with prisms

For C825 Southbound tunnel monitoring project, there are 24 (segments) x 4 (prisms) reference measurement points and 204 (segments) x 4 (prisms) monitoring points. There are 2,736 data points are analyzed automatically within 3 minutes and if any of the points exceed their limits, the users get SMS alerts within 1 minute. The process of analyzing the measured data and users receiving the SMS alerts is achieved within 4 minutes. As there are a huge number of data points to analyze, manual visual checks are very time consuming and prone to errors, if there are 3 measurement cycles per day. Without automatic data analysis and SMS alert, critical time might be lost in using manual data analysis and manual alert system. This in turn can cause expensive construction remedies and delays.

Fig 7 SMS Alert Information

This alert is a simple concept as it checks that the movements do not exceed their preset thresholds. Once that limit has been exceeded, SMS alerts are automatically send out to assign users. Fig 7 shows the SMS alert screen, which gives the prism number, alert status, movement from its datum and time. It is known that the SMS alerts can have hour time delays if they are sent to different service providers during peak periods. The solution, to avoid these important SMS alerts in tunnel movements, is to route these information directly to the dedicated end user service provider networks. This reduces the cross Telco SMS delays from hours to a more consistent SMS delivery time of 30 seconds.

Fig. 8 shows a typical chart and the trigger occurred in the segments in the right prism. However there are no movements in the Left, Track and Crown prisms. Usually these single point movements indicate false alarm after an extensive manual crosschecks with other prisms and past records. This re-verification is still carried out manually. The current automatic algorithm analyzes only the movements of that prism with respect to its own past movements in time. A more intelligent alert analysis is required to avoid such false alerts. This can achieve by analyzing the prism movement's relationship to the prisms within the same segment as well as prisms along the adjacent segments, one segment and another before that affected segment.

Future smarter structural cross checking algorithms will be introduced as more automated tunnel monitoring systems are introduced to avoid overloading the users with SMS alerts. The proposed algorithm will deploy more 3D numerical checks for the following: -

Within the same segment

- Movements in the 4 prisms shifting in space
- Vertical Movements in the Crown and Track for vertical loading
- Horizontal Movements in the Left and Right for horizontal loading

Cross-segments

- Movements in the prisms along the same axes in tunnel

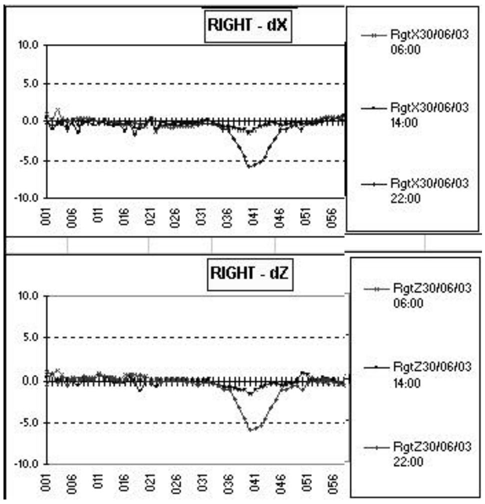

Fig. 8 Chart of Tunnel Movement per cycle

The structural movement checks will help to reduce the false SMS alerts. The system will automatically be analyzed for such information to be sent to the users to help them minimize false alerts and work stoppages.

3.5 System Scalability

The current system design is suitable for handling a number of projects simultaneously. However it is expected that by simply scaling and duplicating the individual systems for different monitoring projects, the cost and effort to maintain the system will be high. The constraints for a scaling up system are the number of physical telephone lines allocated by the service provider, data storage & backup for multiple PCs, different operating system, different revisions of software, software version control, end user interfaces, UPS, power stability and data security with site mirroring.

Fig 9 shows a scalable wireless networked automatic remote monitoring system based upon the eMonitoring concept to overcome the limitations of the current multiple stand-alone systems. The wire-less remote network system has the capacity to handle up to 128 automated remote RTUs for tunnels and structures. It uses extensively the Wireless and Internet public networks infrastructure so that the expansion of remote sites is easier to deploy and supported. By migrating the slower 9,600 bps Global System for Mobile communication (GSM) data line to the 33,600 bps General Packet Radio Service (GPRS) communication, the speed of data transfer will be improved and as well as provide a true on-line connection from the RTU back to the central server.

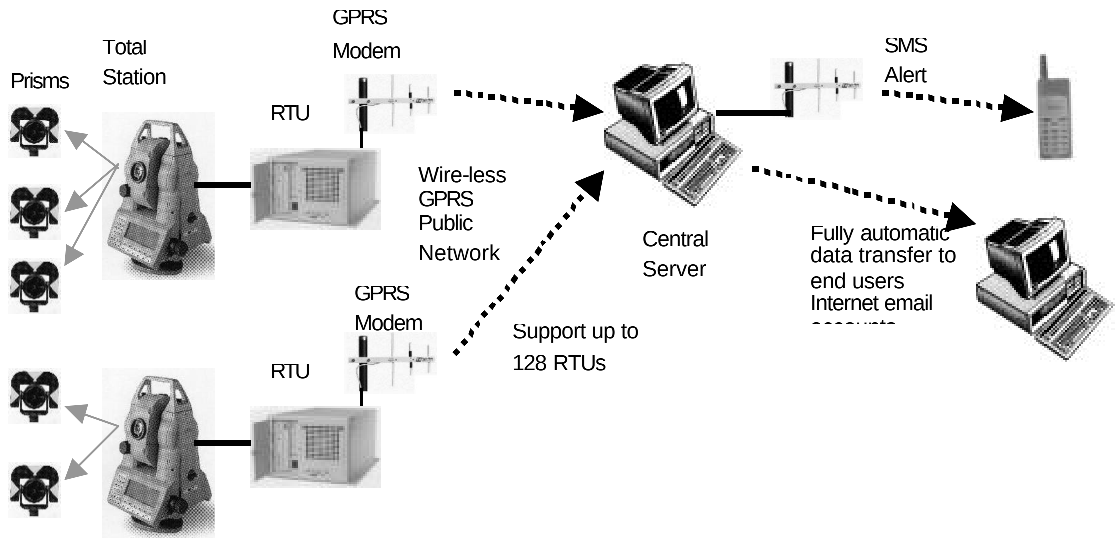

Fig. 9 On line GPRS Wire-less Network Multi RTU Tunnel Monitoring System

4 CONCLUSIONS

With the wider market acceptance of wireless data communication and computer technologies, automation for the construction industry can go beyond office automation. The business advantage of using reliable remote wireless field monitoring systems in projects, which require real time monitoring and alerts systems, is the minimizing of risk at construction sites by providing reliable and timely information to the right people.

ACKNOWLEDGEMENT

The authors would like to thank the Clients, Main-Contractors, Consultants and Supplier for the use their material for this presentation. Special thanks to IDA and the staff of SysEng (S) Pte Ltd and Wisescan Engineering Services Pte Ltd for work carried out in this project.

REFERENCES

Tan, G. H. (2000). eMonitoring Systems, SysEng (S) Pte Ltd.

IDA (2002). Infocomm Development Authority of Singapore, May 2002, Mobile Workforce Call for Collaboration.